Testing minimum energy with powerful radio sources in clusters of galaxies

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Abstract

We analyze *ROSAT* data for cluster gas surrounding powerful radio galaxies, which is well fitted by a "β-model" gas distribution, after allowing for a compact central source. The cluster thermal pressure at the distance of the radio lobes is typically an order of magnitude larger than the lobe minimum pressure. Since radio lobes are sharply-bounded, the missing pressure is not simply entrained intra-cluster gas. Thus the minimum energy in the lobes is a severe underestimate of the actual energy content. We argue that the extra energy is mostly in the form of particles, so that the magnetic field is below equipartition and thus not a major factor in the lobe dynamics. The large departure from minimum energy has far-reaching implications for the nature of AGN central engines and the supply of mechanical energy to the cluster gas.

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1 Introduction

Despite the well-known drawbacks, minimum energies are the foundation for estimates of the energetics of AGN jets and the double-lobed radio sources (DRAGNs) they create. The lobes, lying ~ 100 kpc from the centre of large elliptical galaxies, must be surrounded by gas at 10^7–10^8 K (for simplicity,

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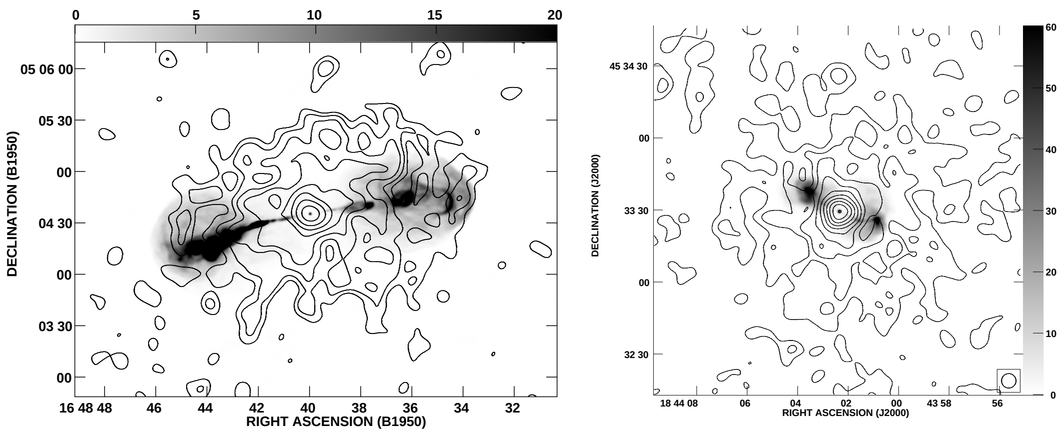

Fig. 1. Left: *ROSAT* HRI contours (separated by factors of $\sqrt{2}$) of the X-ray emission from Hercules A, smoothed with a 10-arcsec gaussian, superimposed on a VLA λ20 cm image from Gizani & Leahy (1999). Right: HRI contours (separated by intervals of 2σ) of 3C 388, smoothed with a 6-arcsec gaussian, on the VLA λ22 cm image from Roettiger et al. (1994).

the "intra-cluster medium"). The ICM confines the lobes either directly by thermal pressure or, as in conventional models for FR IIs, by ram pressure. Hence the ambient pressure $P_{\rm th} = 2.3 n_H kT$ gives a lower limit for the lobe energy density, to be compared with the minimum energy estimate.

In several twin-jet FR Is, $u_{min}/3 \equiv P_{\rm min} \ll P_{\rm th}$, but these jets are believed to be strongly entraining, so pressure support could be dominated by a thermal component not included in $P_{\rm min}$. In contrast, the lobes of FR IIs and the similar "relaxed doubles" have sharp boundaries (e.g. Leahy & Perley 1991), suggesting little entrainment, as expected for cavities produced by powerful, relativistic jets. This is confirmed by the observed holes in the ICM of Cygnus A (Carilli et al. 1994). Only a handful of powerful sources have environments detectable with pre-*XMM* X-ray observatories. We have observed two of them with *ROSAT*, and discuss the results for these and others in the literature. We assume $H_0 = 65$ km s^{-1} Mpc^{-1} and $q_0 = 0$.

2 Observations and results

We observed Hercules A with the PSPC and HRI, and 3C 388 with the HRI (Gizani & Leahy 1999, Leahy & Gizani 1999). Both are identified with cD galaxies at the centres of clusters. In both, the X-ray images (Fig. 1) show compact central peaks, probably due to the AGN. We therefore fitted the X-ray radial profiles with a *ROSAT* point-spread function plus a modified King (β) model, giving a reasonable fit in both cases, with good agreement between HRI and PSPC for Her A.

Table 1
Results of Minimum-energy calculations and β model fits

DRAGN	$\lg(P_{178})$	α	$u_{\rm min}/3$	D	$R_{\rm core}$	β	n_0	kT	Ref
	$\mathrm{W\,Hz^{-1}\,sr^{-1}}$		pPa	kpc	kpc		$10^3\,\mathrm{m^{-3}}$	keV	
Hercules A	27.33	1.01	0.30, 0.38	540	121	0.74	6.5	2.45	1
3C 388	25.68	0.70	0.72, 0.36	92	33	0.53	11	3	2,3
Cygnus A	27.81	0.74	6.7, 8.6	147	41	0.75	65	4	4
3C 295	27.71	0.63	111, 112	34	42	0.56	40	7.1	5,6
3C 28	26.22	1.06	0.81, 0.84	153	50	0.67	20	4.9	7,8,9
3C 310	25.57	0.92	0.019, 0.028	340	84	0.5	2	2.5	7,10

References: (1) Gizani & Leahy (1999); (2) Leahy & Gizani (1999); (3) Roettiger et al. (1994); (4) Carilli et al. (1994); (5) Neumann (1999); (6) Leahy & Spencer (1999); (7) Hardcastle & Worrall (1999); (8) Shibata et al. (1999). (8) Leahy, Bridle & Strom (1996); (10) Leahy & Williams (1984).

We have also taken from the literature similar data for other cases of powerful DRAGNs in cluster-centre galaxies. All objects are more luminous than the FR division and consist of sharply-bounded lobes, although only 3C 295 and Cyg A are truly "classical" doubles. Table 1 lists for our full sample the radio power at 178 MHz (P_{178}), the linear size (D), and the parameters of the model fits to the X-ray data. We list ICM temperatures from *ROSAT* or *ASCA* spectra, except for 3C 310 and 3C 388 where we used the $L_X - T$ relation for clusters of galaxies. We also list $u_{\rm min}/3$ for each lobe, found using the standard formulae (c.f. Leahy 1991). We assume no "invisible" energy (e.g. in protons), a filling factor of unity, a 10 MHz spectral cutoff, and an inclination of 50° for the lobe axes. We used the spectral index α of the integrated emission below 1 GHz, where the lobes dominate.

Fig. 2 plots $P_{\rm min}$ against $P_{\rm th}$ at a "typical" (see caption) position for the lobe. Clearly the two are related, but in most objects $P_{\rm min} \simeq 0.1 P_{\rm th}$. The two objects with the highest pressures and smallest discrepancy are the prototype classical doubles Cyg A and 3C 295, which are expected to be strongly *over-pressured*, which means that $P_{\rm min}$ **is in general least an order of magnitude below the true lobe pressure**. Our sample is clearly biased to high external pressures; but there is no reason why the ratio of true to minimum pressure should depend on the actual value of the pressure, so the bias should not affect our conclusion. The hotspot $P_{\rm min}$, not plotted here, is substantially above $P_{\rm th}$ for Cyg A and 3C 295 but in 3C 388 is still less than $P_{\rm th}$. However in FR II models the whole lobe and not just the hotspot is expected to be over-pressured.

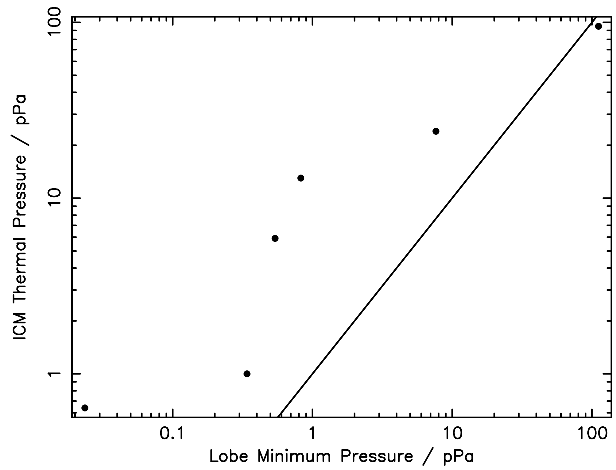

Fig. 2. Plot of the average (across the two lobes) minimum pressure against the ambient thermal pressure at a radius equal to two-thirds of the distance from the core to the ends of the lobes. The line shows $P_{\rm th} = P_{\rm min}$.

3 Discussion

Inverse-Compton radiation (ICR) has now been detected from several radio lobes (Harris et al. 1994, Feigelson et al. 1994, Kanada et al. 1995, Tsakiris et al. 1996, Tashiro et al. 1998, Brunetti et al. 1999). The implied magnetic fields, B, are generally within 60% of conventional minimum-energy values; there are no cases where detectable ICR is predicted for $B \lesssim B_{\rm me}$ but not seen. **This suggests $B \approx B_{\rm me}$ in typical radio lobes**. In contrast, our results would require $B \approx 3B_{\rm me}$ to retain equipartition, while numerical simulations suggest that B is below equipartition (e.g. Clarke 1993). These results could all be reconciled if the energy is dominated by "invisible" particles such as protons or low-energy electrons. For 3C 388, with its rather flat low-frequency spectra, it is not even enough to extend the energy spectrum to Lorentz factor $\gamma = 1$; however e^--e^+ jets may be saved if the observed power-law is only a "tail" on a relativistic-Maxwellian energy distribution (the lobe temperature must be relativistic if fed by relativistic jets).

Rawlings & Saunders (1991) used minimum-energy estimates and spectral ages to derive a relation between jet power, Q, and narrow-line luminosity in 3CR radio galaxies: $Q \simeq 100 L_{\rm NLR} \approx 550 L_{\rm [O\,III]}$. Similarly, Falcke et al. (1993) relate accretion disc luminosity (effectively the big blue bump) to [O III] "magnitude" for PG quasars, which can be decoded as: $L_{\rm disc} \simeq 430 L_{\rm [O\,III]}$. The Falcke et al. relation appears to hold irrespective of radio-loudness. Jackson & Browne (1990) show that [O III] is somewhat anisotropic, with quasars 5–10 times more luminous in [O III] than corresponding radio galaxies; however, as the Rawlings & Saunders correlation is partly based on the more isotropic [O II], we estimate a factor of 3 offset between the effective [O III] luminosities in the above two relations. To be conservative, we assume that the AGN bolometric luminosity

L_{AGN} is twice that of the big blue bump, to allow for the IR and X-ray peaks. Thus for radio loud objects, the Rawlings & Saunders result implies $Q \simeq 0.2 L_{AGN}$. A primary uncertainty in the spectral age, the use of $B_{\rm me}$, is strongly supported by the ICR results. A systematic underestimate of ages of up to about 3 is possible from mixing within the lobes (Tribble 1993). Even allowing for that, **our calibration of $u_{\rm min}$ implies that the jet kinetic luminosity in radio-loud AGN is at least as large as the bolometric luminosity of the AGN, and may substantially exceed it**. There is no reason why this should not be so, as jets and thermal radiation are independent by-products of accretion; jets are not powered by the AGN radiation.

If jets are a primary energy loss mechanism of AGN in cluster-centre ellipticals (which are always radio-loud if active at all), then much of the accretion energy produced by the growth of the central black hole does work on the cluster gas, heating it. Taking $L \approx 0.1 \dot{M} c^2$, we assume half of this goes into the jet, and (consistent with Rawlings and Saunders) that half of the jet power does work on the cluster as opposed to being ultimately radiated as very-low-frequency radio waves, the total energy supplied to the cluster gas is $0.025 M_{\bullet} c^2$. If central black holes really follow the Magorrian et al. (1998) relation, this corresponds to 1.5×10^{-4} times the galaxy rest mass, more than ten times the available energy from supernova-driven winds (c.f. Ponman et al. 1999). Thus jets must have had a dramatic effect on the cluster gas at early epochs, where most AGN activity and, presumably, black hole growth occurred.

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